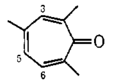
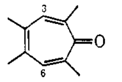
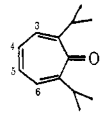
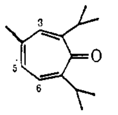
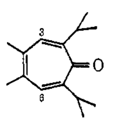
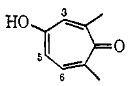
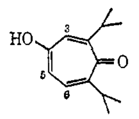
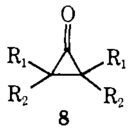
Table II. Physical Properties of New Troponoids

Compound	Yield,[a] %	Mp, °C	Uv, nm[b] (log ε)	Ir,[c] cm^{-1}	Nmr, δ[d,e]
	51	Oil	237 (4.19), 333 (3.89), 342 (3.86)	1559	2.29 (bs, 9 H, CH_3), 6.6–6.9 (m, 1 H, H_5), 7.1–7.3 (m, 2 H, H_3, H_6)
	66	88–89[f]	239 (4.25), 339 (3.76), 346 (3.76)	1553	2.28 (bs, 12 H, CH_3), 7.30 (bs, 2 H, H_3, H_6)
	63	Oil	238 (4.24), 243 (4.20), 325 (3.65), 340 (3.55)	1571	1.19 (d,[g] 12 H, CH_3), 3.1–3.8 (m, 2 H, $\geqslant$CH), 6.7–7.3 (A_2B_2 pattern, H_3, H_4, H_5, H_6)
	50	Oil	238 (4.31), 328 (3.80)[h]	1572	1.20 (d,[g] 6 H, CH_3), 1.22 (d,[g] 6 H, CH_3), 2.36 (s, 3 H, CH_3), 3.2–3.9 (m, 2 H, $\geqslant$CH), 6.6–6.9 (m, 1 H, H_5), 6.9–7.1 (m, 2 H, H_3, H_6)
	53	47–48[f]	240 (4.32), 334 (3.86)[h]	1563	1.19 (d,[g] 12 H, CH_3), 2.27 (s, 6 H, CH_3), 3.2–3.8 (m, 2 H, $\geqslant$CH), 7.00 (s, 2 H, H_3, H_6)
	55	168–170[i]	238 (4.34), 368 (4.28)[j]	1466[k]	2.03 (s, 3 H, CH_3), 2.13 (s, 3 H, CH_3), 6.66 (dd, 1 H, H_5), 7.62 (d, 1 H, H_3), 7.63 (d, 1 H, H_6)[l,m]
	46	160–161[i]	241 (4.31), 371 (4.29)[j]	1457[k]	1.08 (d,[g] 6 H, CH_3), 1.11 (d,[g] 6 H, CH_3), 3.0–3.6 (m, 2 H, $\geqslant$CH), 6.41 (dd, 1 H, H_5), 7.05 (d, 1 H, H_3), 7.12 (d, 1 H, H_6)[l,n]

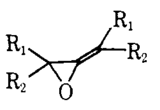
[a] Isolated yield based on the 4-cycloheptenone. [b] Taken in H_2O unless otherwise stated. [c] Recorded in $CHCl_3$ except where otherwise indicated. Only the strongest band in the 1700–1400-cm^{-1} region is recorded. [d] Obtained in $CDCl_3$, unless a solvent is specified (60 MHz). [e] b = broad, s = singlet, d = doublet, m = multiplet. [f] From petroleum ether. [g] $J = 7.0$ Hz. [h] In MeOH. [i] From ethyl acetate. [j] In 0.1 *N* NaOH. [k] As Nujol mull. [l] In DMSO-d_6. The spectrum could also be interpreted as that of the tautomeric 3,5-dialkyl-γ-tropolone. [m] $J_{35} = 2.5$ Hz and $J_{56} = 10.5$ Hz. [n] $J_{35} = 2.0$ and $J_{56} = 10.0$ Hz.

rivatives obtained in a similar manner are given in Table II.

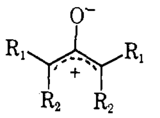
The annelation reaction which executed a key step of the new troponoid synthesis could *a priori* be accounted for by assuming the intervention of cyclopropanones **8**, allene oxides **9**, or the corresponding mesomeric zwitterions **10**,[8] produced by dehalogenation of dibromo ketones. However, free cyclopro-



8



9



10

panones add only to cyclic 1,3-dienes such as cyclopentadiene and furan, yielding bicyclic adducts, and *do not* react with acyclic conjugated dienes.[9] Furthermore, control experiments showed that reduction of the dibromo ketones **1–3** with zinc–copper couple in DMF, under which conditions formation of **9**[10] or **10**[11] would be expected, in the presence of 20-fold excess of 2,3-dimethylbutadiene, gives no trace of cycloheptenones. Thus mechanisms involving free **8**, **9**, or **10** seem unlikely. The reaction might proceed by way of the iron complexes bearing these species and diene as coordinated ligands. Alternatively, the coupling reaction might be achieved sequentially *via* iron enolates formed by an electron-transfer process,[12] or discrete σ-bonded organoiron compounds arising from oxidative addition[13] of the C–Br bond to iron carbonyl.

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(8) N. J. Turro, *Accounts Chem. Res.*, **2**, 25 (1969).

(9) N. J. Turro, S. S. Edelson, J. R. Williams, T. R. Darling, and W. B. Hammond, *J. Amer. Chem. Soc.*, **91**, 2283 (1969).

(10) H. M. R. Hoffmann and R. H. Smithers, *Angew. Chem.*, **82**, 43 (1970).

(11) (a) H. E. Zimmerman, D. Dopp, and P. S. Huyffer, *J. Amer. Chem. Soc.*, **88**, 5352 (1966); (b) H. E. Zimmerman and D. S. Crumine, *ibid.*, **90**, 5612 (1968); (c) T. M. Brennan and R. K. Hill, *ibid.*, **90**, 5615 (1968).

(12) Formation of nickel enolate was postulated in the reaction of α-bromo ketones and nickel carbonyl: E. Yoshisato and S. Tsutsumi, *ibid.*, **90**, 4488 (1968).

(13) J. P. Collman, *Accounts Chem. Res.*, **1**, 136 (1968).

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The Influence of Translational Entropy of Activation on Reaction Rates in Isotopic Solvents

Sir:

Hitherto, the influence of entropy has not been considered to be a major factor when different rates of reaction occur in isotropic solvents. In the case of water, pertinent discussions have emphasized the importance of zero-point energy,[1,2] ion–solvent interaction in the transition state,[3] and the structural free-energy difference in the initial state solvation shells.[4] For the most part, analytical arguments have centered around H-bonding vibrational frequencies,[1,2] ion–water libration frequencies,[5] solubilities,[6] and heat capacities of activation.[4]

Experimental evidence indicates that both $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$ are susceptible to variation when isotopic solvents are employed.[7–10] The isotopic dependence of $\Delta H^{\ddagger}$ can be attributed to the difference in zero-point energies of the isotopes, but the theoretical significance of the dependence of $\Delta S^{\ddagger}$ has been overlooked. Variation in this parameter could be due to differences in the temperature coefficient of the dielectric constant for the solvent, but at least for light and heavy water these differences are small.[11] A close examination of the partition functions for entropy reveals that the rotational terms are complex and undeterminable, whereas the vibrational terms are negligible compared to the term for translation.[12] Differences in the librational frequencies of light and heavy water have been shown to contribute to the solvent isotope effect and have been used to calculate the entropies of solutions of ions.[6] Except for the fluoride ion, the entropy of solution of an ion is greater in D_2O, and the entropy difference between H_2O and D_2O is less than one unit. Thus, it appears that if libration frequencies could be obtained for water in the presence of a reactant and its transition complex, isotopic differences would be small. It is assumed, therefore, that a major portion of the kinetic isotope effect will be due to the translation of bound solvent over the free-energy barrier.

Consider the reactions

$$AB\cdot y(H_2O)_n + x(H_2O)_n \rightleftharpoons AB^{\ddagger}\cdot(x+y)(H_2O)_n \longrightarrow \text{products} \quad (1)$$

$$AB\cdot y(D_2O)_n + x(D_2O)_n \rightleftharpoons AB^{\ddagger}\cdot(x+y)(D_2O)_n \longrightarrow \text{products} \quad (2)$$

where AB is any reactant and $AB^{\ddagger}$ is its transition state. The reactant is solvated with y units of associated water and the transition state is solvated with $(x + y)$ units. Therefore, x units of water are gained or lost when the reactant attains the transition state. The quantity n represents the average number of water molecules in an associated unit. At 30° this is about 4.6 for pure water,[13] but this value will vary with conditions and is probably not the unit involved in solvation.

From statistical mechanics, the entropy of translation for 1 mol of a perfect gas is[12]

$$S_{tr} = 2.2868(5\log T - 2\log p + 3\log m) - 2.3135 \quad (3)$$

where T is the absolute temperature, p is the pressure in atmospheres, and m is the mass of the molecule. The translational entropy of activation for eq 1 and 2 will be

$$\Delta S^{\ddagger}_{tr(H_2O)} = 2.2868[5\log T - 2\log p + 3\log(m_1 + (x+y)m_2)] - 2.3135 - 2.2868[5\log T - 2\log p + 3\log(m_1 + ym_2)] + 2.3135) - x[2.2868(5\log T - 2\log p + 3\log m_2) - 2.3135] \quad (4)$$

and

$$\Delta S^{\ddagger}_{tr(D_2O)} = 2.2868[5\log T - 2\log p + 3\log(m_1 + (x+y)m_3)] - 2.3135 - 2.2868[5\log T - 2\log p + 3\log(m_1 + ym_3)] + 2.3135) - x[2.2868(5\log T - 2\log p + 3\log m_3) - 2.3135] \quad (5)$$

respectively, where m_1 is the mass of AB, m_2 is the mass of $(H_2O)_n$, and m_3 is the mass of $(D_2O)_n$.

Upon subtracting eq 4 from 5, one finds

$$\Delta S^{\ddagger}_{tr(D_2O)} - \Delta S^{\ddagger}_{tr(H_2O)} = 2.2868\left[3\left(\log\frac{m_1 + (x+y)m_3}{m_1 + (x+y)m_2} + x\log\frac{m_2}{m_3} + \log\frac{m_1 + ym_2}{m_1 + ym_3}\right)\right] \quad (6)$$

Any deviation from ideal behavior which might occur would have to be included in the pressure terms. However, these terms cancel, as they would be approximately equal for isotopic molecules. Thus, eq 6 does not contain either pressure or temperature, and the ordered structure in a solvated system must be related directly to the total mass of the unit which is translated over the free-energy barrier.

Table I. Calculated Differences in Translational Entropy of Activation for Reactions in H_2O and D_2O, Using Equation 7

Units of water bound, x	$\Delta S^{\ddagger}_{sie}$ $(\Delta S^{\ddagger}_{D_2O} - \Delta S^{\ddagger}_{H_2O})_{Tr}$	Influence on k_{H_2O}/k_{D_2O}
1	−0.32	1.18
2	−0.63	1.37
3	−0.95	1.61
4	−1.26	1.89
5	−1.58	2.22
6	−1.89	2.59
7	−2.22	3.06
8	−2.52	3.56
9	−2.84	4.18
10	−3.15	4.88

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(3) C. G. Swain and E. R. Thornton, *ibid.*, **84**, 822 (1962).

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(5) C. G. Swain and R. F. Bader, *Tetrahedron*, **10**, 182 (1960).

(6) E. R. Thornton, *Annu. Rev. Phys. Chem.*, **17**, 365 (1966).

(7) L. Tseng, Ph.D. Thesis, University of North Dakota, Grand Forks, N. D., 1968.

(8) J. G. Winter and J. M. W. Scott, *Can. J. Chem.*, **46**, 2887 (1968).

(9) (a) B. N. Hendy, W. A. Redmond, and R. E. Robertson, *ibid.*, **45**, 2071 (1967); (b) L. Teindl, R. E. Robertson, and S. E. Sugamori, *ibid.*, **47**, 3397 (1969).

(10) O. W. Marko, M.S. Thesis, University of North Dakota, Grand Forks, N. D., 1967.

(11) C. D. Hodgman, Ed., "Handbook of Chemistry and Physics," 43rd ed, Chemical Rubber Publishing Co., Cleveland, Ohio, 1961, pp 2550–2551.

(12) S. Glasstone, "Theoretical Chemistry," Van Nostrand, Princeton, N. J., 1948, Chapter 8.

(13) J. Morgan and B. E. Warren, *J. Chem. Phys.*, **6**, 666 (1938).

Table II. Some Experimental Values of $\Delta S^{\ddagger}_{\mathrm{sie}}$ for Hydrolytic Reactions in Light and Heavy Water

Reactant	$\Delta H^{\ddagger}$, kcal mol^{-1}		$\Delta S^{\ddagger}$, cal mol^{-1} deg^{-1}		k_{H_2O}/k_{D_2O}	$\Delta S^{\ddagger}_{\mathrm{sie}}$	Ref
	H_2O	D_2O	H_2O	D_2O			
O-(Chloroacetyl)salicylic acid[a]	14.62 ± 0.08	14.84 ± 0.08	−23.58 ± 0.27	−24.51 ± 0.27	2.35	−0.9	*d*
Methyl trifluoroacetate[b]	10.60 ± 0.03	10.48 ± 0.05	−32.3 ± 0.3	−34.0 ± 0.4	3.48	−1.7	*e*
Ethyl trifluoroacetate[b]	10.53 ± 0.03	11.08 ± 0.03	−34.5 ± 0.3	−35.1 ± 0.3	3.54	−0.6	*e*
tert-Butyl trifluoroacetate[b]	25.44 ± 0.06	26.08 ± 0.05	+13.7 ± 0.5	+15.5 ± 0.0	1.19	+1.8	*e*
α-Bromoisobutyrate	28.96	29.86	+20.6	+23.2	1.26	+2.6	*f*
2,4-Dinitrophenylacetate[c]	12.04	9.49	−37.2	−48.8	1.48	−11.6	*g*

[a] 10% v/v dioxane, pH 6. [b] Neutral solution. [c] 10% v/v dioxane, pH 5.6. [d] Reference 7. [e] Reference 8. [f] Reference 9a. [g] Reference 10.

Since m_1 is usually much larger than m_2 or m_3, and if x or y are not very large, then the first and last terms in eq 6 are approximately equal. This equation becomes

$$\Delta S^{\ddagger}_{\mathrm{sie}} = \Delta S^{\ddagger}_{\mathrm{tr(D_2O)}} - \Delta S^{\ddagger}_{\mathrm{tr(H_2O)}} = 6.8604x(\log m_2/m_3) \quad (7)$$

where $\Delta S^{\ddagger}_{\mathrm{sie}}$ is defined as the solvent isotope effect on the translational entropy of activation due to differences in solvation between the reactant(s) and the activated complex. Values of $\Delta S^{\ddagger}_{\mathrm{sie}}$ calculated for light and heavy water by assigning interger values to x in eq 7 are listed in Table I. They were calculated on the basis that the degree of solvation of reactant and the association of solvent are the same for both isotopes. That is, the values of x, y, and n are equal for H_2O and D_2O. Although the values of $\Delta S^{\ddagger}_{\mathrm{sie}}$ given in Table I are not very great, they have a pronounced effect on the ratio k_{H_2O}/k_{D_2O}. Furthermore, the sign of $\Delta S^{\ddagger}_{\mathrm{sie}}$ can be used as evidence to indicate whether additional solvent is bound or released in the activated state. When solvent is released x is negative and the values of $\Delta S^{\ddagger}_{\mathrm{sie}}$ are positive. However, when solvent is bound, x is positive and $\Delta S^{\ddagger}_{\mathrm{sie}}$ negative. To verify these findings some experimental evidence is cited below.

So far two systems have been studied in this laboratory,[7,10] but examples also can be found in the literature.[8,9] We measured the activation parameters for *O*-(chloroacetyl)salicylic acid at several pH and pD values.[7] The most reliable measurements were obtained in the pH- or pD-independent region 4.5–8. The results at pH 6 (pD 6.4) are listed in Table II. The raw data were analyzed by computer techniques using the least-squares method. Within experimental error the activation enthalpy is slightly greater for the D_2O system as expected. However, the entropy term is more negative. If a portion of the large negative entropy of activation for this system is caused by solvation, then the activated state must be more polar and upon activation additional solvent becomes bound.[14] This means that, according to eq 7, $\Delta S^{\ddagger}_{\mathrm{sie}}$ should be negative. The result in Table II for $\Delta S^{\ddagger}_{\mathrm{sie}}$ is −0.9 eu. With reference to Table I, this suggests approximately three additional units of water are bound in the transition state. This finding for *O*-(chloroacetyl)salicylic acid is sustantiated by the results for the neutral hydrolysis of methyl and ethyl trifluoroacetates as reported in the literature.[8] These esters (Table II) have negative $\Delta S^{\ddagger}$ and $\Delta S^{\ddagger}_{\mathrm{sie}}$ values which suggests additional solvent is bound in the activated state. It is interesting to note that the methyl ester hydrolyzes slower in D_2O even though it has a lower $\Delta H^{\ddagger}$ than in H_2O. Therefore, the slower rate in D_2O is due entirely to a decrease in $\Delta S^{\ddagger}$. According to Table I, five or six additional solvent units are bound in the transition state for this ester.

In contrast with systems having negative entropies, *tert*-butyl trifluoroacetate[8] and α-bromoisobutyrate[9] listed in Table II have positive $\Delta S^{\ddagger}$ and positive $\Delta S^{\ddagger}_{\mathrm{sie}}$ values. On the basis of these positive values, it can be postulated that solvent is released when these systems attain a transition condition. The fact that solvent is lost during activation tends to lower the k_{H_2O}/k_{D_2O} ratio to near unity.

In conclusion, it can be said that thermodynamic activation parameters must be closely scrutinized before any firm conclusions can be drawn as to the mechanistic significance of the value of k_{H_2O}/k_{D_2O}. The characterization of a chemical reaction by solvent isotope studies appears to involve changes in enthalpy and entropy, and both must be weighed accordingly. In the past only differences in activation enthalpy have been considered and correlated with zero-point energies, whereas our present calculations infer that differences in activation entropies also must be considered. If additional solvent (compared to the reactant) is translated over the free-energy barrier, the translational entropy contribution to the rate constant will be less in the heavier isotopic solvent. On the other hand, if solvent is lost during transition, the entropy contribution to the rate constant will be greater in the heavier isotopic solvent.

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The Tricyclo[3.2.0.0^{2,7}]hept-3-yl (3-Psinortricyclyl) Cation[1]

Sir:

The highly strained *exo*- and *endo*-tricyclo[3.2.0.0^{2,7}]hept-3-yl systems (**3** and **5**) provide structures whose

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(14) K. J. Laidler, "Chemical Kinetics," McGraw-Hill, New York, N. Y., 1965, Chapter 5, p 228.

(1) The name "psinortricyclyl" (for "pseudonortricyclyl") is intro-